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Performance evaluation of a natural convective-cooled concentration solar thermoelectric generator coupled with a spectrally selective high temperature absorber coating

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A B S T R A C T

Solar energy can be directly harnessed for power generation by using solar thermoelectric generator (STEG) technology, which comprises of solar absorbers integrated with thermoelectric materials. STEGs behave as solid state heat engines, which can utilize the heat energy of the sun to produce a temperature gradient across a thermoelectric device, which is in turn converted to electrical energy. In this paper, we focus on investigating the performance of the solar absorber subsystem that employs a high temperature spectrally selective coating on a stainless steel substrate. We have performed temperature measurements on the absorber coating exposed to solar irradiation flux at different optical concentration ratios (10–100) and validated the experimental data using a numerical heat transfer model in COMSOL Multiphysics. This has been combined with the high temperature emittance measurements of the coating to develop a predictive efficiency model for the STEG system as a function of the thermoelectric figure of merit at a hot side temperature range of 100–500 °C. Further, we have experimentally examined the performance of a natural convective cooled STEG consisting of a series combination of three commercial Bi_2Te_3 thermoelectric modules coupled to the selective absorber coating. The maximum power generated from the STEG has been measured at different concentration ratios and the peak efficiency of the system has been calculated in the feasible temperature range of the thermoelectric module.

1. Introduction

Growing energy demand across the world has necessitated the need to explore new technologies for power generation. The sun's energy presents great potential to serve as a viable alternative source of power as it is a renewable and sustainable source of energy [1]. Solar photovoltaic systems and large scale solar thermal power systems are the most common technologies currently being used to harness solar power [2–5]. In addition to these technologies, the area of solar thermoelectrics represents another option that can convert the sun's heat to useful electrical energy [6], especially for small scale applications like micro-power systems.

Thermoelectric generators have historically been used primarily in waste heat recovery systems but they can also be an effective means of small scale power generation when integrated with solar power. Such generators are called solar thermoelectric generators (STEGs) and use thermal energy to create a temperature gradient across the hot and cold junctions of a thermoelectric material which is used to generate voltage as per the principle of Seebeck effect [7]. STEGs typically work as solid-state heat engines and therefore act as a portable power generating system for standalone rooftop arrangements. They do not have any requirement of moving parts or working fluids for operation and, therefore, have captured interest in recent times [8,9].

The performance of an STEG system is largely dependent on two of its components: the solar absorber and the thermoelectric material. The need to maximize the performance of each of these components leads us to realize the important role played by the materials employed in the system. Spectrally selective absorbers are used so as to absorb maximum amount of radiation incident on their surface (i.e., high absorptance, α), while at the same time emitting less radiation (i.e., low thermal emittance, ε) to ensure a high efficiency of the absorber [10,11]. Therefore, they must be stable and retain their selective properties at high temperatures to minimize radiation losses. Similarly, high figure of merit (ZT) materials need to be employed since the thermoelectric efficiency of the system is directly dependent on the value of ZT in the

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temperature range of operation [12]. Moreover, to achieve large temperature gradients, techniques like optical and thermal concentration have to be used so as to concentrate the solar beam to produce a large value of irradiation flux. Therefore, the system efficiency of an STEG is governed by interplay of various parameters, which need to be optimized to achieve a low cost and effective design for power generation.

The pioneering research on STEGs for power generation was carried out by Maria Telkes in 1954. Her experiments demonstrated 3.35% system efficiency under optical concentration with a lens employing the best Zn–Sb and Bi alloy combination of that period [13]. This reported efficiency was not bettered until 2011 when Kraemer et al. [14] reported an efficiency of 4.6% for nanostructured bismuth telluride (Bi_2Te_3) thermoelectric materials using solar selective absorbers and thermal concentration by employing a large absorber. With the arrival of high ZT materials and the need for further exploring the performance potential of STEG technology, there have been various recent works in this field. Studies featuring the use of nanostructured materials and thermal concentration, like the work by Kraemer et al. and innovative designs employing segmented and cascaded thermoelectric materials to optimize material performance as carried out by McEnaney et al. [15] have shed light on various experimental improvements in design and approach. Further, various works like the studies performed by Ram and Amatya [16] and Pereira et al. [17] have also been dedicated to modeling and simulation of STEG performance using thermodynamic models and finite element techniques that seek to optimize experimental methods and validate experimental observations.

In our present study, we have evaluated the performance of an STEG that uses a commercial Bi_2Te_3 thermoelectric module coupled with a high temperature spectrally selective absorber coating. In the first part of the paper, we have determined the thermal performance of our coating under different optical concentration ratios using a Fresnel lens to determine the steady state temperatures that can be attained and sustained by it. In the subsequent sections, we have made theoretical predictions of the re-radiation losses, absorber efficiency and the net STEG system efficiency using the temperature–concentration ratio correlation of our coating. We have also carried out high temperature emittance measurements of the coating and incorporated this emittance variation while predicting the system efficiencies as a variation with ZT in the temperature range of 100–500 °C. Finally, we have experimentally evaluated the performance of an STEG that uses this absorber coating as a collector, integrated with three thermoelectric modules in a stacked arrangement. A finned aluminum heat sink has been used to facilitate natural convective cooling to produce the desired temperature gradient in our experiments and subsequent measurements of voltage, power output and system efficiency have been carried out.

2. Experimental details

The absorber coatings were deposited on stainless steel (SS) substrates (dimensions 35 mm × 35 mm × 2 mm) by a Four-Cathode Reactive Unbalanced Direct Current (DC) Magnetron Sputtering System with 7.25″ diameter targets. Absorptance and emittance of the coatings were measured using Solar Spectrum Reflectometer (model SSR) and Emissometer (Model AE) of M/s. Devices and Services. The emittance was measured at 82 °C. The optical properties of the absorber coatings were also measured using UV–vis–NIR (Cary 500i, Varian) and FTIR (Nicolet 6700, Thermo Scientific). As will be discussed later, the emissivity at high temperatures was also measured for the absorber coating.

To understand the usefulness of such a coating, initial theoretical calculations were performed in which the absorber efficiency of a system using a selective coating was compared to that of a system using a polished stainless steel surface as an absorber. According to Stefan–Boltzmann's law, any surface radiates energy to its surroundings at a rate proportional to its emittance and the fourth power of its temperature (T^4), which is a thermal loss for any energy system. To establish the suitability of a spectrally selective coating in such an application, analysis of these re-radiation losses was also performed by including the high temperature emittance measurements carried out.

In the experimental study, the steady state temperatures attainable using the selective absorber coating were determined under concentrated solar irradiation flux using a Fresnel lens at various optical concentration ratios. The experiments were performed in Bengaluru, India when the Direct Normal Irradiation (DNI) as calculated from Ref. [18] was about 865 W/m^2. To avoid optical tracking issues, the measurements were taken during noon time. A suitable fixture was fabricated for the outdoor rooftop setup for carrying out the temperature measurements. A Fresnel lens, 49×65 cm^2 was used for concentrating the incident solar irradiation so as to produce a large value of flux (up to 100 suns) at the surface of the absorber. The solar selective substrate was mounted on a ceramic brick, a very good thermal insulator, so as to prevent heat loss due to conduction and obtain a high value of surface steady state temperature.

To study the variation of the absorber temperature with optical concentration ratio, the setup was designed so as to enable changing of distance between the sample and the lens. This was done to enable change of focus area, and therefore change in the optical concentration. A Pt-100 temperature sensor, having an approximate error of ± 2 °C, connected to a temperature display indicator was clamped to the substrate. During the experiment, the entire frame at any point of time was adjusted such that the direct radiation from the sun fell normally on the absorber. This was to ensure that peak solar flux was achieved at all times. The sample was allowed to attain steady state and the temperature readings were taken. These values were validated using a numerical heat transfer simulation performed in COMSOL Multi-physics.

In another set of experiments, the solar selective substrate was used in an STEG system to directly convert solar energy to electrical energy for micro-power applications. A schematic diagram of the experimental setup has been shown in Fig. 1(a). A commercial bismuth telluride HZ-2 thermoelectric module manufactured by Hi-Z Technology Inc. having 97 p–n thermo-couples was fixed below the substrate. A finned aluminum heat sink was used below the module to enhance the natural air convective cooling at its bottom surface due to increased surface area.

For the initial open circuit voltage tests, the output terminals of the module were connected to a digital voltmeter and the voltage measurements were recorded at different hot side temperatures by varying the concentration ratio. However, as no external cooling mechanism was employed, this arrangement with a single module could not yield a sufficient temperature gradient to generate desired output voltages. Therefore, three thermoelectric modules were connected electrically in series and placed in a thermally parallel stacked arrangement below the solar absorber as shown in Fig. 1(b). Thermal grease was applied on each surface of the modules and the bottom of the absorber so as to ensure electrical insulation and near perfect thermal contact. By varying the optical concentration ratio of the incident solar radiation, the different voltage readings obtained were recorded. Fig. 1(c) shows the STEG system with aluminum heat sink, Fresnel lens and voltage display indicator. The concentrated focal spot of the solar irradiation on the spectrally selective coating can be seen in Fig. 1(d).